Turbulent Mixing Parameterizations for Oceanic Flows and Student Support

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LONG-TERM GOALS

The long-term goal of these two closely related research projects is to formulate robust turbulence parameterizations that are applicable for a wide range of oceanic flow conditions.

OBJECTIVES

The primary objectives of these projects are to bridge the gap between parameterizations/models for small-scale turbulent mixing developed from fundamental direct numerical simulations (DNS) and grid turbulence experiments to geophysical scale models with an emphasis on making progress towards improved turbulent parameterizations in the ocean and (ii) to develop a quantitative understanding of the impact of obstacles on the lateral mixing of momentum and scalars in oceanic flows.

APPROACH

Our main approaches are to use theoretical modeling efforts to formulate parameterizations and then use model-data comparisons, to test our formulations. As a separate exercise, we are also performing highly-resolved two-dimensional and three-dimensional simulations of flow around obstacles to investigate and elucidate the fundamental mechanisms responsible for turbulent mixing; and improve the efficacy of existing parameterizations for turbulent mixing.

WORK COMPLETED

In FY2014, most of our effort has been on formulating a general framework for parameterizing stably stratified shear-flow turbulence and our work has recently been published as a journal article in *Physics of Fluids (*Mater and Venayagamoorthy 2014a*)*. The second half of our effort in this FY has been on data analysis of field scale observations of small scale turbulence measurements from different sites. Through collaborations that the PI has forged with Dr. Louis St. Laurent at WHOI and Dr. James Moum at Oregon State University, Benjamin Mater (the PhD candidate on this project) has performed extensive analysis of turbulence measurements in an effort to examine classical overturning length scales (e.g. Thorpe and Ozmidov scales) and their relationships to kinetic energy dissipation rate especially in strong turbulent forcing environments such as slope convection. In particular, the PI's collaboration with Dr. St. Laurent had provided Mr. Mater with a unique opportunity to examine turbulence measurements made in internal wave dominated environments using free-falling microstructure profilers. The PI joined the scientific team in July 2011 for a 3-week long research expedition to the Luzon Passage in South China Sea to conduct microstructure study as part of the ONR sponsored Internal Waves in Straits Experiment (IWISE). This is one of most energetic internal wave induced mixing regions with overturns of the order of hundreds of meters high (Alford *et al.* 2011).

We have also done an analysis to highlight important ambiguities in single parameter schemes for mixing efficiency in geophysical flows using a multi-paramter framework (in line with the work by Mater and Venayagamoorthy 2014). Parameterizations based on the gradient Richardson number (Ri), the buoyancy Reynold number (Re_b) and the turbulent Froude number (Fr_t) are considered. The diagnostic ability of these parameters is examined using published data from both direct numerical simulations and field observations. This work has been published in *Geophysical Research Letters* (see Mater and Venayagamoorthy 2014b for further details).

RESULTS

As a direct extension to the work published in Mater *et al.* (2013), we have included mean shear S to bring the discussion closer to the realm of oceanic flows in which turbulence can be decaying or growing. Hence, we took into consideration the additional regimes using the shear parameter ST_L, where $T_L = k/\varepsilon$ is the turbulence time scale and/or the gradient Richardson number Ri. In the limit of high Reynolds numbers, we can conceptualize the flow in an NT_L - ST_L space as shown in Figure 1 through which lines of constant Ri are constructed. Within this conceptual framework, we have assumed critical values in NT_L, ST_L and Ri so that the two-dimensional space is de-lineated into the well-cited regimes of shear and buoyancy dominance, but also a regime in which these background influences are absent or minimal that we entitle the "unforced" regime. In this regime the flow trends toward isotropy in that any sustained "forcing" by shear or stratification is not felt. Therefore, in such a state, Ri becomes an irrelevant concept. A common example of this kind of flow is unstratified turbulence generated by a grid. Critical values in the parameters are initial estimates informed from classical studies on flow stability and stationarity. The choice of $Ri_c \approx 0.25$ follows from classic shear layer stability analysis (Miles 1961) and has been shown to be a criterion for stationarity in homogeneous shear flows (e.g. Rohr et al. 1988). Choice of a critical value in the shear parameter follows from findings that $ST_{L,c} \approx 3.3$ in the log layer of unstratified channel flow where production and dissipation are in approximate balance (see Pope (2000)) and at mid-depth in stationary wind tunnel turbulence (Saddoughi and Veeravalli 1994). Recently, Chung and Matheou (2012) published data suggesting this value is approached in the unstratified limit of stationary homogeneous turbulence. The typical values chosen for Ri_c and $ST_{L,c}$ imply $NT_{L,c} = O(10^0)$ which is in agreement with our earlier findings as discussed in Mater *et al.* (2013) regarding Thorpe scale behavior in the stratified, shear-free limit.

We then examined various numerical simulations and laboratory/field datasets to show their distribution on the parameter space as shown in Figure 1 and to determine the relationships between the overturning scale (i.e. the Ellison/Thorpe length scales) and related fundamental length scales such as the Ozmidov length scale L_O and the turbulent kinetic energy shear and buoyancy length scales L_{kS} and L_{kN}, respectively. The details of the datasets and analysis are given in Mater and Venayagamoorthy

(2014a). Our findings indicate that the overturning scale given by the Ellison length scale L_E appears to be strongly correlated with the turbulent kinetic energy length scales scales L_{kS} and $L_{kN.}$ as shown in Figures 2 through 3.

We have also provided an alternative formulation for the diapycnal mixing (i.e. diapycnal diffusivity K_d) based on the premise that the turbulent kinetic energy can be inferred from the overturns. Comparisons reveal that the proposed formulation yields better agreement with exact diffusivities (see Figure 4a) in contrast to diffusivities inferred using the commonly invoked assumption of equality between overturning Thorpe length scale and the Ozmidov scale (see Figure 4b). Further details can be found in Mater and Venayagamoorthy 2014a.

The second thrust of our work is to investigate the impact of obstacles on the flow dynamics and lateral mixing of scalars as well as momentum. To this end, we are performing highly resolved numerical simulations to quantify the lateral mixing and transport of a passive scalar around porous cylindrical obstacle in uniform and oscillatory flows with/without density stratification.

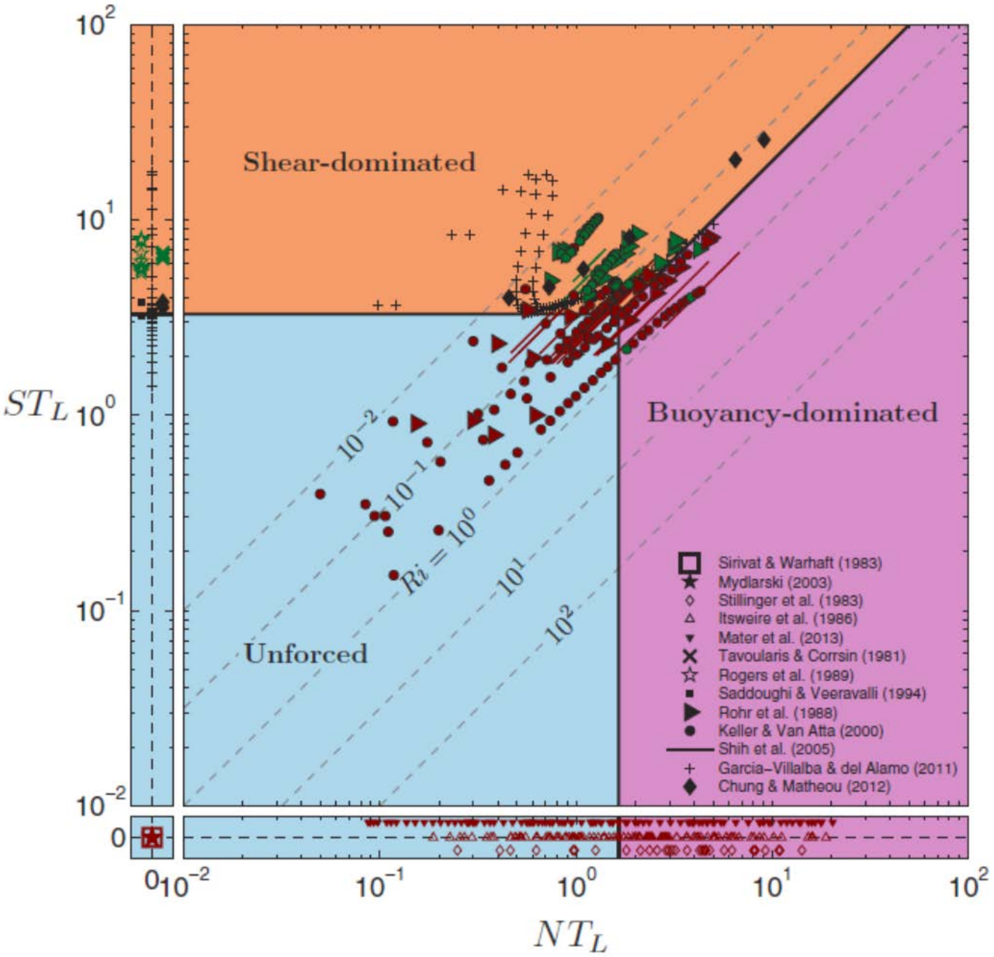

Figure 1: Parameter space for interpretation of high-Reynolds number turbulence. Growing turbulence (Dk/Dt > 0) shown in green, stationary turbulence (Dk/Dt ≈ 0) shown in black, and decaying turbulence (Dk/Dt < 0) shown in red. Select data points have been offset from $NT_L = 0$ or $ST_L = 0$ for clarity. Lines delineating regimes are first order approximations

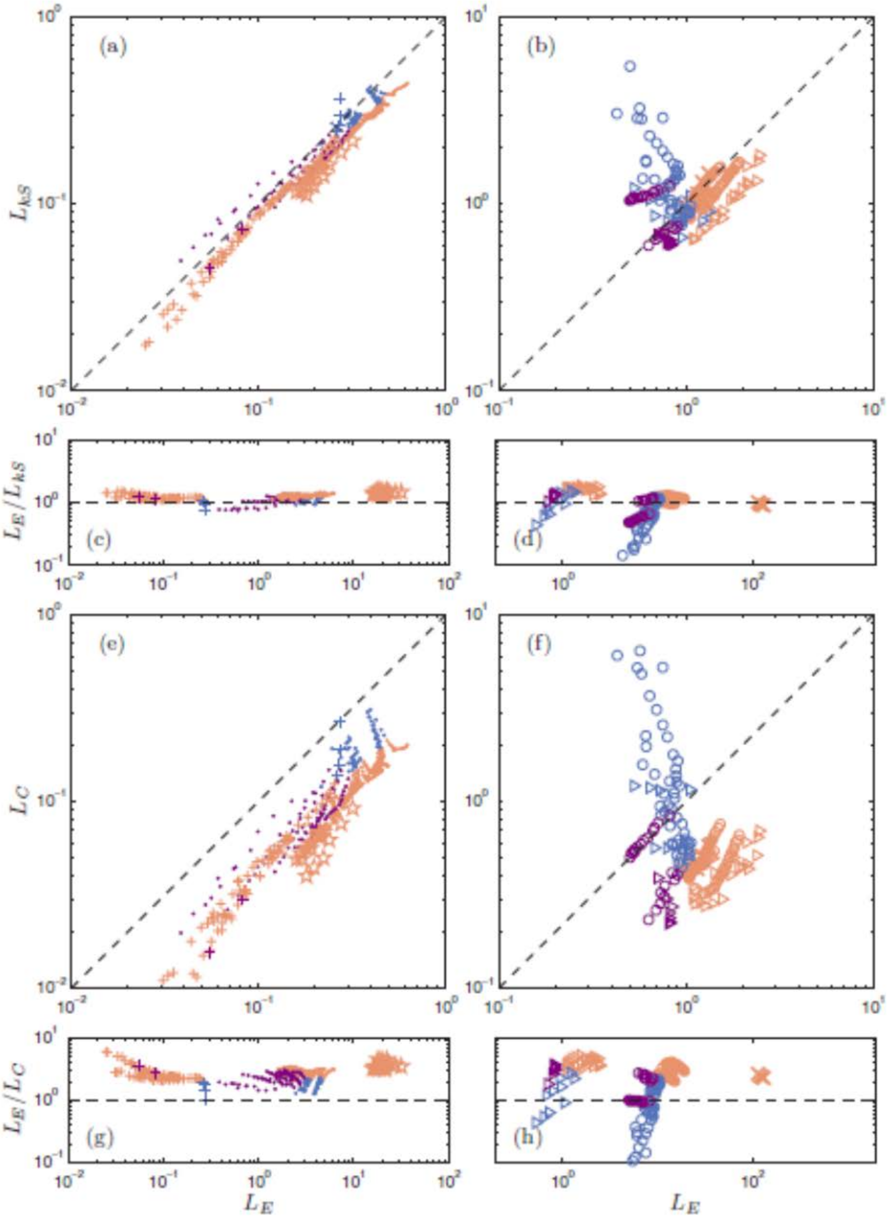

Figure 2: Comparisons of the fundamental shear length scales, L_{kS} and L_C, to L_E. Left panels show DNS data in normalized units [(a), (c), (e), (g)]; right panels show experimental data in cm [(b), (d), (f), (h)]. Symbols are noted in Figure 1.

IMPACT/APPLICATIONS

Our work is motivated by oceanic studies of diapycnal mixing where observed overturns can be used to infer turbulent quantities that are pertinent to mixing but difficult to measure reliably. This project will contribute to an improved understanding of small-scale mixing processes and development of better parameterizations of such processes for applications in large-scale oceanic numerical simulation models where such processes are not explicitly resolved.

RELATED PROJECTS

The PI has another ONR funded project on internal wave driven mixing and transport in the coastal ocean where the goal is to investigate mixing from breaking internal waves interacting with topography. Hence there is some natural overlap between these two projects

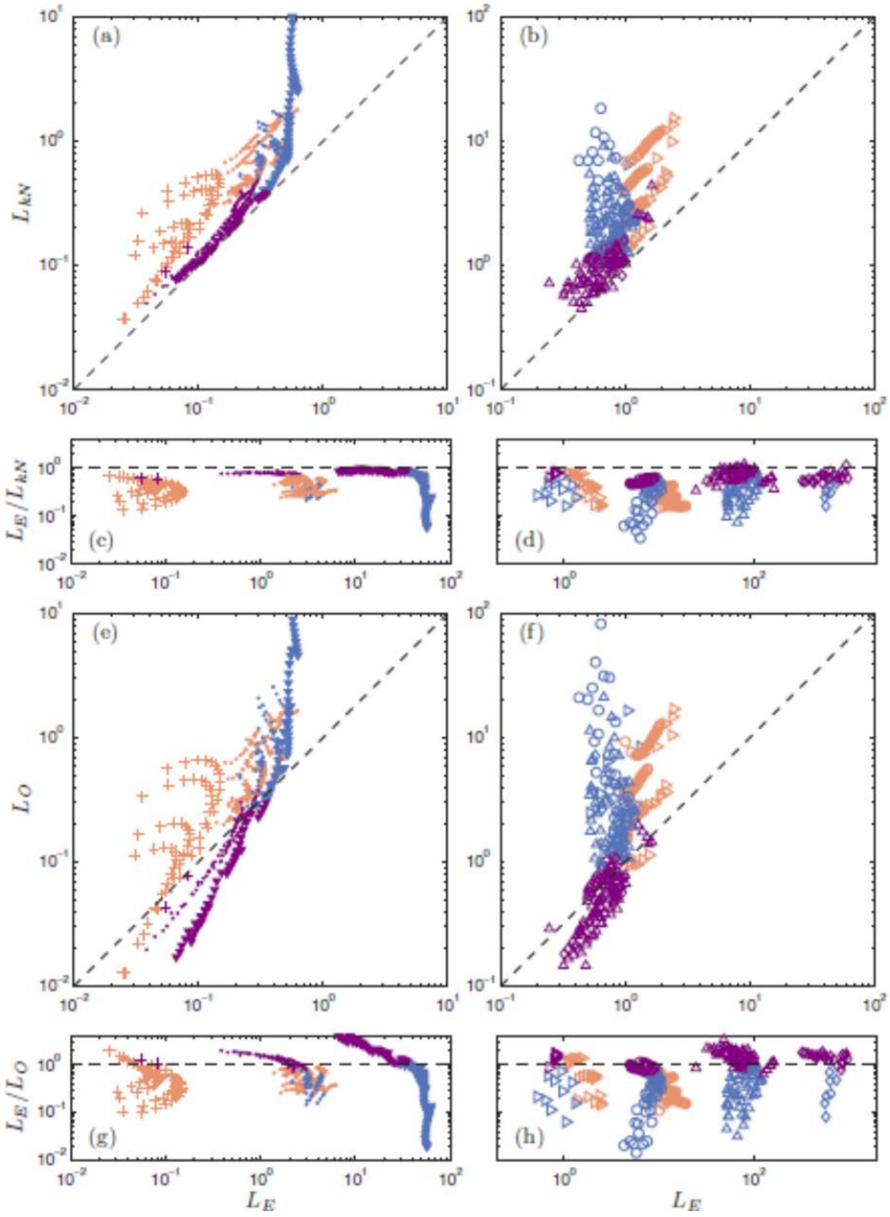

Figure 3: Comparisons of the fundamental buoyancy length scales, L_{kN} and L_O, to L_E. Left panels show DNS data in normalized units [(a), (c), (e), (g)]; right panels show experimental data in cm [(b), (d), (f), (h)]. Symbols are noted in Figure 1.

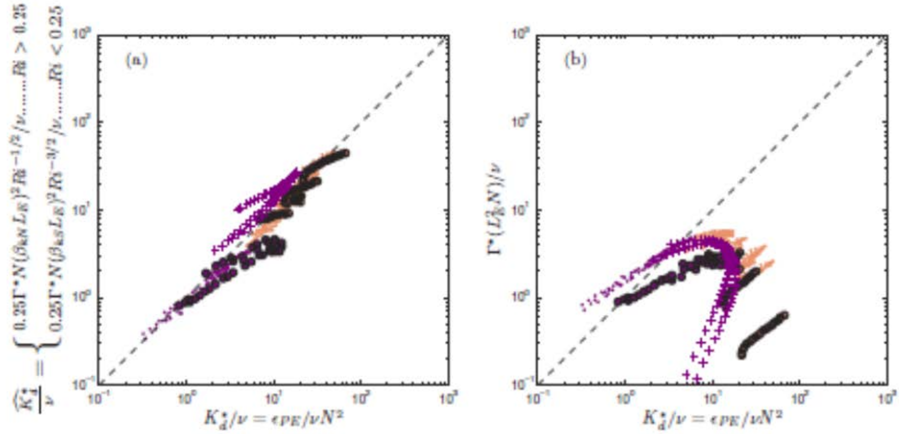

Figure 4:Comparison of estimated and actual density diffusivity K_d^* normalized by molecular viscosity ν. Panel (a) shows the results using a formulation that based the overturning length scale L_E as a measure of the turbulent kinetic energy and panel (b) shows the results using a formulation uses the widely used assumption of near equality of overturning length scale and the Ozmidov scale L_O.

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PUBLICATIONS

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Mater, B. and Venayagamoorthy, S. K. 2013. “Abstract: H36.00001 : Relevancy of the buoyancy Reynolds number in stably stratified turbulence”, In Transactions of the 66th Annual Meeting of the Division of Fluid Dynamics American Physical Society, 24-26 November 2013, Pittsburgh, Pennsylvania, USA.

Manuscripts in Revision

Mater, B. D., Venayagamoorthy, S. K., St. Laurent, L. and Moum, J. N. 2014. “Biases in Thorpe scale estimation of turbulence dissipation from large overturns in the ocean”, in revision for *Journal of Physical Oceanography*.

HONORS/AWARDS/PRIZES

2014 – Francois N. Frenkiel Award, American Physical Society, Division of Fluid Dynamics - in recognition of significant contributions to fluid mechanics that have been published in Physics of Fluids during the preceding year by young investigators. This award was given for an article published in the *Physics of Fluid Journal* the entitled “Relevance of the Thorpe scale in stably stratified turbulence” by Mater, B. D., Schaad, S. M. and Venayagamoorthy, S. K. 2013.

2014 - Faculty Excellence in Teaching Award, Department of Civil and Environmental Engineering, CSU.

2014 - Invited participant, Indo-American Frontiers of Eng. Symposium, National Academy Engineering.